N92-22520

LIFE PREDICTION TECHNOLOGIES FOR AERONAUTICAL PROPULSION SYSTEMS

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SUMMARY

Fatigue and fracture problems continue to occur in aeronautical gas turbine engines. Components whose useful life is limited by these failure modes include turbine hot-section blades, vanes, and disks. Safety considerations dictate that catastrophic failures be avoided, while economic considerations dictate that noncatastrophic failures occur as infrequently as possible. The decision in design is therefore making the tradeoff between engine performance and durability. The NASA Lewis Research Center has contributed to the aeropropulsion industry in the area of life prediction technology for over 30 years, developing creep and fatigue life prediction methodologies for hot-section materials. At the present time, emphasis is being placed on the development of methods capable of handling both thermal and mechanical fatigue under severe environments. Recent accomplishments include the development of more accurate creep-fatigue life prediction methods such as the total strain version of Lewis' strainrange partitioning (SRP) and the HOST-developed cyclic damage accumulation (CDA) model. Other examples include the development of a more accurate cumulative fatigue damage rule - the double damage curve approach (DDCA), which provides greatly improved accuracy in comparison with usual cumulative fatigue design rules. Other accomplishments in the area of high-temperature fatigue crack growth may also be mentioned. Finally, we are looking to the future and are beginning to do research on the advanced methods which will be required for development of advanced materials and propulsion systems over the next 10 to 20 years.

PERFORMANCE VERSUS DURABILITY

Fatigue and fracture problems continue to occur throughout aeronautical gas turbine engines. Safety considerations dictate that life-threatening catastrophic failures be avoided, and economic considerations dictate that noncatastrophic failures occur as infrequently as possible. The failure rate, however, can be related directly to the performance extracted from the machine. We thus have the perennial dichotomy: performance versus durability (fig. 1). Because the primary driver for aeropropulsion is performance, we must view lack of adequate durability as a constraint to the desired performance. Knowledge of both aspects is necessary to understand and quantify the tradeoffs between the two. Performance may take a variety of forms, including for example, higher thrust-to-weight ratio or better fuel efficiency. Similarly, durability is constrained by factors which include excessive deformation, thermomechanical fatigue, and fracture. Our ability to accurately predict the durability of a structure is much less sophisticated than our ability to accurately predict structural performance. This is due primarily to three factors. First, in the case of structural performance, analytical solutions exist, in most cases, which can be applied with high accuracy. In the case of structural durability, analytic solutions for the majority of failure modes simply don't exist. Secondly, in the case of performance, verification of performance goals occurs early in the design and development cycle, whereas durability aspects generally require long-term testing for verification. Nowhere is the tradeoff more critical than in the turbine hot section, where multiple failure modes are present in varying degree.

Figure 2 illustrates typical components that have exhibited histories of limited durability. Compressor blades, combustor liners, guide vanes, turbine blades, disks, shafts, bearings, and spacers are just a few of the more common components that have exhibited cyclic crack initiation, propagation, and fracture phenomena. These failure phenomena arise because of repeated thermal and/or mechanical loading induced by the service cycle.

LEWIS RESEARCH CENTER CONTRIBUTIONS

At Lewis Research Center, we have aided the aeropropulsion industry by concentrating on developing fracture and elevated-temperature fatigue life methods (fig. 3). One of the earliest contributions was the development of the basic plastic strain-life fatigue law, discovered independently by Manson in 1953 (ref. 1) and by Coffin in 1954 (ref. 2). In an effort to provide a means of assessing the fatigue behavior of materials from data commonly assessable to engineers, the method of universal slopes was developed (ref. 3) in 1965. The universal slopes equation predicts the fatigue behavior of a metallic material based on the material's monotonic tensile properties, namely, the ultimate tensile strength and ductility.

In the development of high-temperature creep-fatigue life prediction techniques, a number of enhancements to creep-rupture parameters and to the time-and-cycle-fraction rule were made. One of the more highly developed methods included strainrange partitioning (SRP), a method which views the creep-fatigue problem in terms of an inelastic strain measure derived from four fundamental straining (or loading) cycles and employs a damage interaction rule to arrive at a life assessment. The ductility-normalized strainrange partitioning (DN-SRP) (ref. 4) provided designers a means of estimating creep-fatigue life from monotonic tensile and creep-rupture data. The total-strain version (TS-SRP) provided a means of predicting creep-fatigue life in terms of the total strains experienced by the structure (ref. 5). As aeropropulsion became more sophisticated and advanced materials were developed, we increased our level of intensity and degree of sophistication in life prediction modeling. At the present time, emphasis is placed on methods capable of dealing with both thermal and mechani cal fatigue under severe environments. Life prediction methods under development include those designed to handle anisotropic materials such as directionally-solidified (DS) or single-crystal materials, as well as improvements addressing thermomechanical fatigue. The bithermal testing technique, originated and developed at Lewis, has shown considerable promise. The bithermal test is one which is substantially easier to perform as well as to interpret (ref. 6). Many of the first order behaviors of TMF are captured in the bithermal experiment. We are also looking to the needs of the future and are beginning to do research on the advanced methods that will be required of advanced materials and propulsion systems over the next 10 to 20 years. In this context, models of damage evolution for composite materials and models which integrate crack initiation, crack growth and fracture models are being pursued.

HIGH-TEMPERATURE FATIGUE CRACK INITIATION

A comparison of the predictive accuracy of two relatively recent (1983, 1984) isothermal life prediction methods for fatigue crack initiation (0.030-in.-length surface crack): the HOST cyclic damage accumulation (CDA) model developed by Pratt & Whitney under contract to Lewis (ref. 7), and the total strain versions of Lewis' strainrange partitioning (TS-SRP) (ref. 5), is shown in figure 4. Note the rather sizeable factors of 3, and hence, our inability to predict the high-temperature, low-cycle fatigue lives of coupons of a cast nickel-base turbine alloy. Factors of safety of nearly an order of magnitude on average life would have to be applied if these methods were to be used in a design situation. While this appears to be a very large factor, it is considerably less than would be required by alternate methods.

COMPLEX LOADING AND CUMULATIVE DAMAGE

Mission profiles resolve into complex thermal and mechanical loading histories on many components (fig. 5). Components whose lives are limited as a result undergo creep and fatigue in varying and interacting degrees, which eventually lead to failure. One such typical component is a hot-section turbine blade.

When considering the life of components subjected to complex mechanical loading histories, it is common to use a fatigue crack initiation life criterion in conjunction with a suitable damage accumulation expression. Traditionally, the damage accumulation expression used is the classical linear damage rule (ref. 8). While this rule simplifies life prediction calculations, it can often lead to unconservative designs, especially under certain loading conditions. An advancement in increasing the accuracy of life predictions by using a nonlinear damage accumulation rule was made at Lewis recently. This new expression, called the double damage curve approach (ref. 9), accounts for loading level dependence in damage evolution. The resulting increase in predictive accuracy is substantial, as much as nearly an order of magnitude improvement over the linear damage rule (fig. 6).

HIGH-TEMPERATURE FATIGUE CRACK PROPAGATION

High- and low-temperature cyclic crack propagation life predictions based on the concepts of path-independent integrals and crack tip oxidation mechanisms have been developed under NASA Lewis sponsorship for turbine alloys (ref. 10, fig. 7). This life prediction method is the result of several years of research conducted by H. W. Liu of Syracuse University under the HOST program sponsorship of NASA Lewis. Note again the rather sizeable scatter of factors of 3 on crack propagation rate even for well-controlled laboratory coupon tests.

COMBUSTOR LINER STRUCTURAL AND LIFE ANALYSIS

An application of the Lewis-originated creep-fatigue life prediction method, strainrange partitioning (for crack initiation), is shown in figure 8. Pratt & Whitney modified the approach to suit their unique requirements and used the method in the design and evaluation of combustor liners in the JT9D high-bypass-ratio engine (ref. 11). Factors of about 2 in cyclic lifetime are noted. This remarkably good accuracy is obtained, in part, by the manner in which the Pratt & Whitney version of the method is calibrated to the failure behavior of real hardware. The variation in predicted lives results from different engine usage which can be accommodated by the predictive method.

TURBINE BLADE STRUCTURAL AND LIFE ANALYSIS

In another application of the Lewis-originated creep-fatigue life prediction method, strainrange partitioning, the General Electric Company analyzed an air-cooled turbine blade, making an assessment of expected service life (ref. 12). This particular blade, a first-stage, high-pressure turbine blade, is subjected to cyclic thermal straining in the tip cap region because of the service history involved (fig. 9). After conducting a thermal analysis and a nonlinear structural analysis of the cap region, an assessment of component life was performed. The analysis was supplemented by laboratory experiments on the blade alloy for the temperature-strain history calculated from the analysis. Strainrange partitioning was found to predict component life over a range which spanned the observed service life.

BRITTLE MATERIALS DESIGN METHOD

The design of brittle ceramics differs from that of ductile metals because of the inability of ceramic materials to redistribute high local stresses caused by inherent flaws. Random flaw size and orientation require that a probabilistic analysis employing the weakest link theory be performed if the component reliability is to be determined. The lack of adequate design technology, such as general purpose design programs, standards, nondestructive evaluation (NDE) expertise, and codes of procedure has prompted NASA Lewis to initiate research focused on ceramics for heat engines at the beginning of this decade. One of the early accomplishments of this effort has been the development of the unique, public-domain design program called Structural Ceramics Analysis and Reliability Evaluation (SCARE) (fig. 10). It is still under development, with new enhancements in improved fast fracture and time-dependent reliability analysis being added and validated.

NONDESTRUCTIVE EVALUATION (NDE) TECHNOLOGY

The need for nondestructive materials characterization is indicated where local properties are critical or where the presence, identity, and distribution of potentially critical flaws can only be assessed statistically. In the latter case, flaws can be so microscopic, numerous, and dispersed that it is impractical to resolve them individually. Large populations of nonresolvable flaws may interact with each other (e.g., surface versus volume flaws) or with morphological anomalies. These interactions would be manifested as degraded bulk properties (e.g., deficiencies in strength and toughness). Although a structure may be free of discrete critical flaws, it may still be susceptible to failure because of inadequate or degraded intrinsic mechanical properties. This can arise from faulty material processing and/or degradation under aggressive service environments. It is important, therefore, to have nondestructive methods for quantitatively characterizing mechanical properties. Figure 11 describes the use of NDE methods.

CONCLUDING REMARKS

The NASA Lewis Research Center has been actively involved in developing life prediction technology to address durability problems in aeronautical gas turbine engines. Current research programs are addressing the problem of thermal and mechanical fatigue, and a number of predictive methods have been developed which possess greater accuracy. As the aerospace field moves toward higher performance propulsion systems resulting in the introduction of new materials and configurations (e.g., composites), the Center is embarking on a program of research to address the unique problems these materials and their operating environments present.

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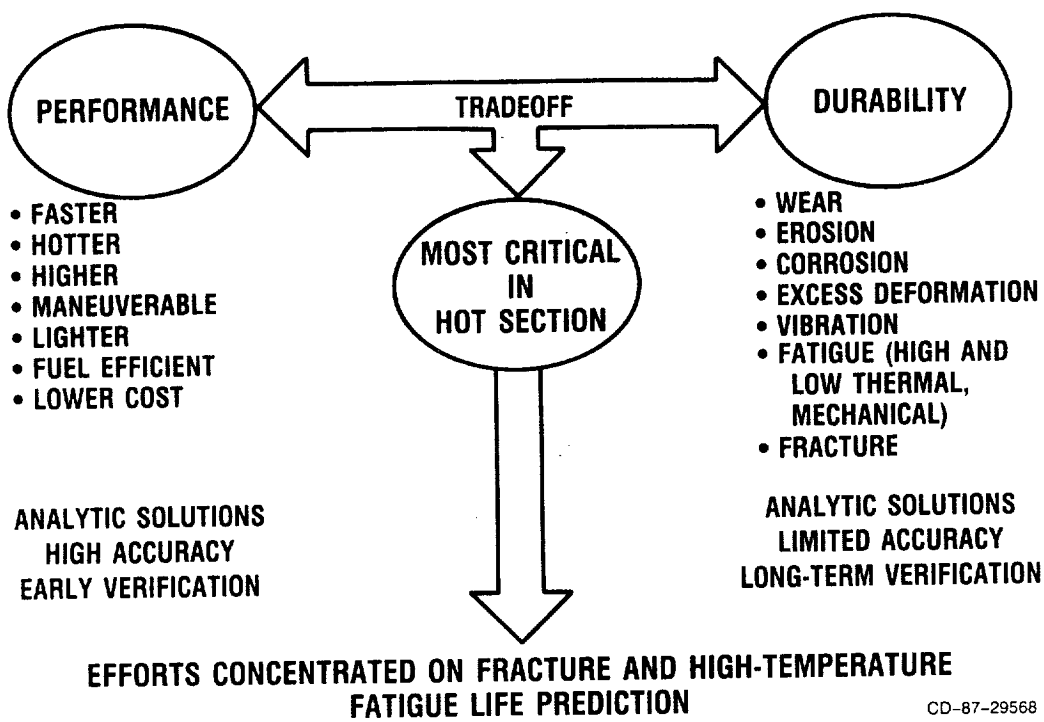


Figure 1. - Performance versus durability.

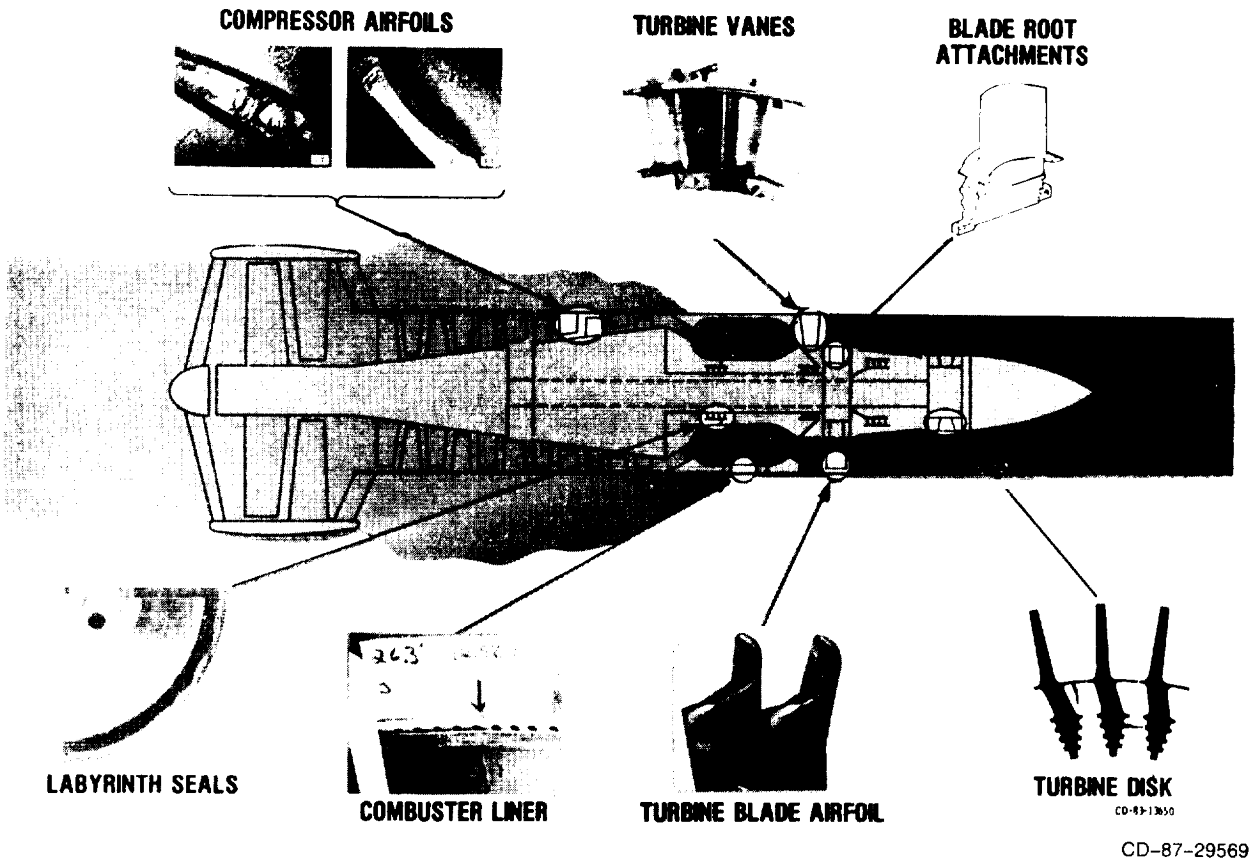


Figure 2. - Gas turbine fatigue and fracture problem areas.

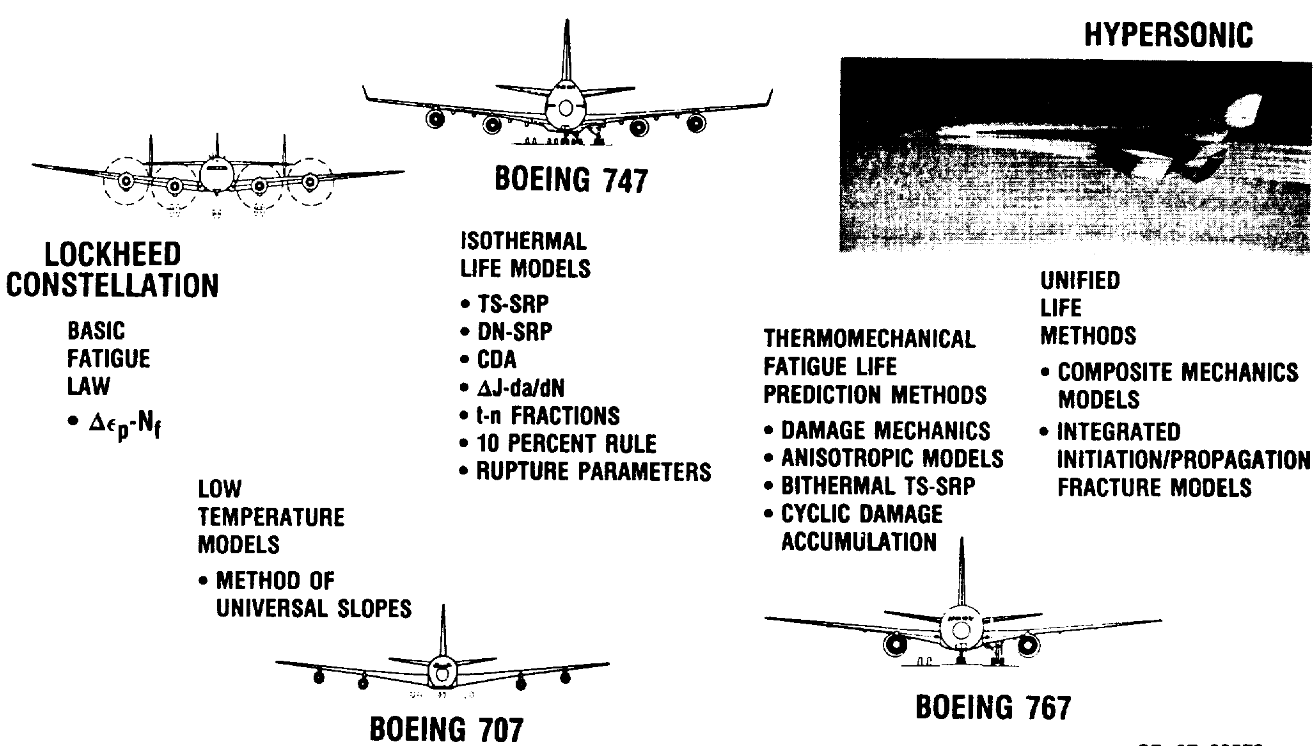
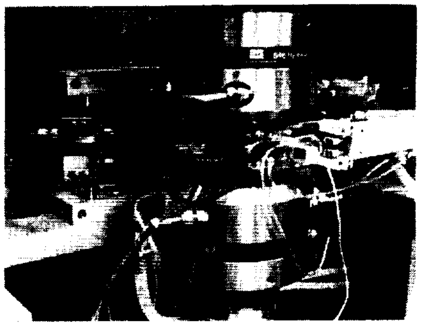
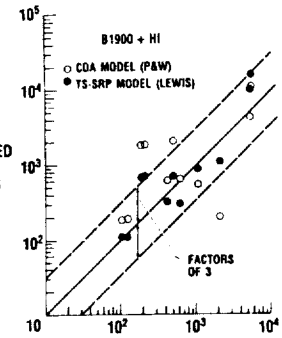


Figure 3. - Lewis Research Center has contributed to fatigue research since the 1950's.



ISOTHERMAL VERIFICATION



CYCLIC DAMAGE ACCUMULATION (CDA) MODEL

$$P_{net} - \left[\int_0^N \frac{dD}{dN}\right]_{Ref} \times \left\{\left(\frac{\sigma_t}{\sigma_{t_{Ref}}}\right)\left(\frac{\Delta\sigma}{\Delta\sigma_{Ref}}\right) + \left[\left(\frac{\Delta\sigma_{Ref}}{\Delta\sigma}\right)\left(\frac{\sigma_t}{\sigma_{t_{Ref}}}\right)\right]^{a'} \times \left[\left(\frac{t}{t_{Ref}}\right)^{c'} - 1\right]\right\} dN = 0$$

TOTAL STRAIN, STRAINRANGE PARTITIONING (TS-SRP)

$$\Delta\epsilon = K_{ij}(C')^n N_f^b + C' N_f^c$$

$$C' = \left[\Sigma F_{ij}(C_{ij})^{1/c}\right]^c$$

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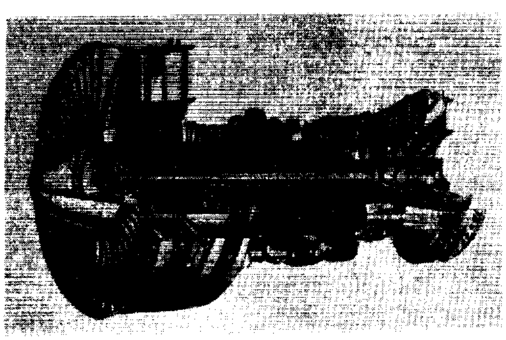
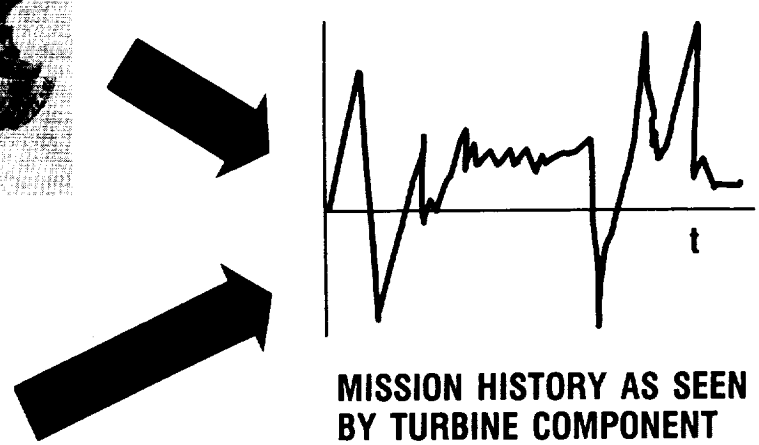
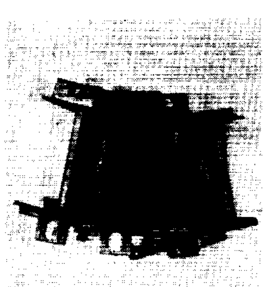
Figure 4. - High-temperature fatigue crack initiation.

ENGINE





MISSION HISTORY AS SEEN BY TURBINE COMPONENT



TURBINE COMPONENT

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Figure 5. - Mission history produces complex component loading histories.

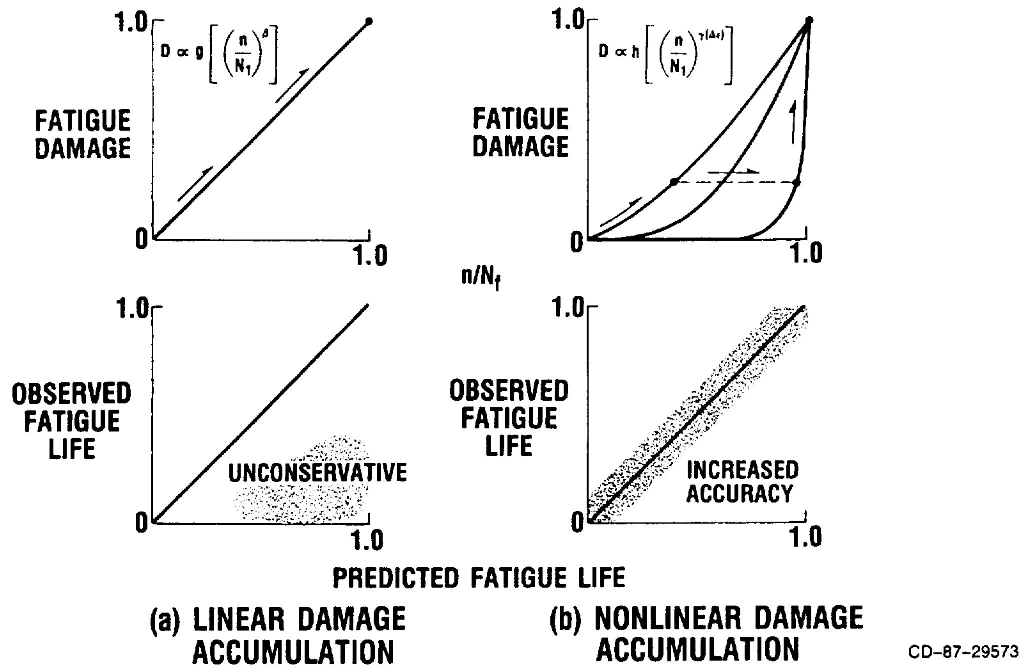

Figure 6. - Lewis nonlinear damage accumulation theories accurately model cumulative fatigue.

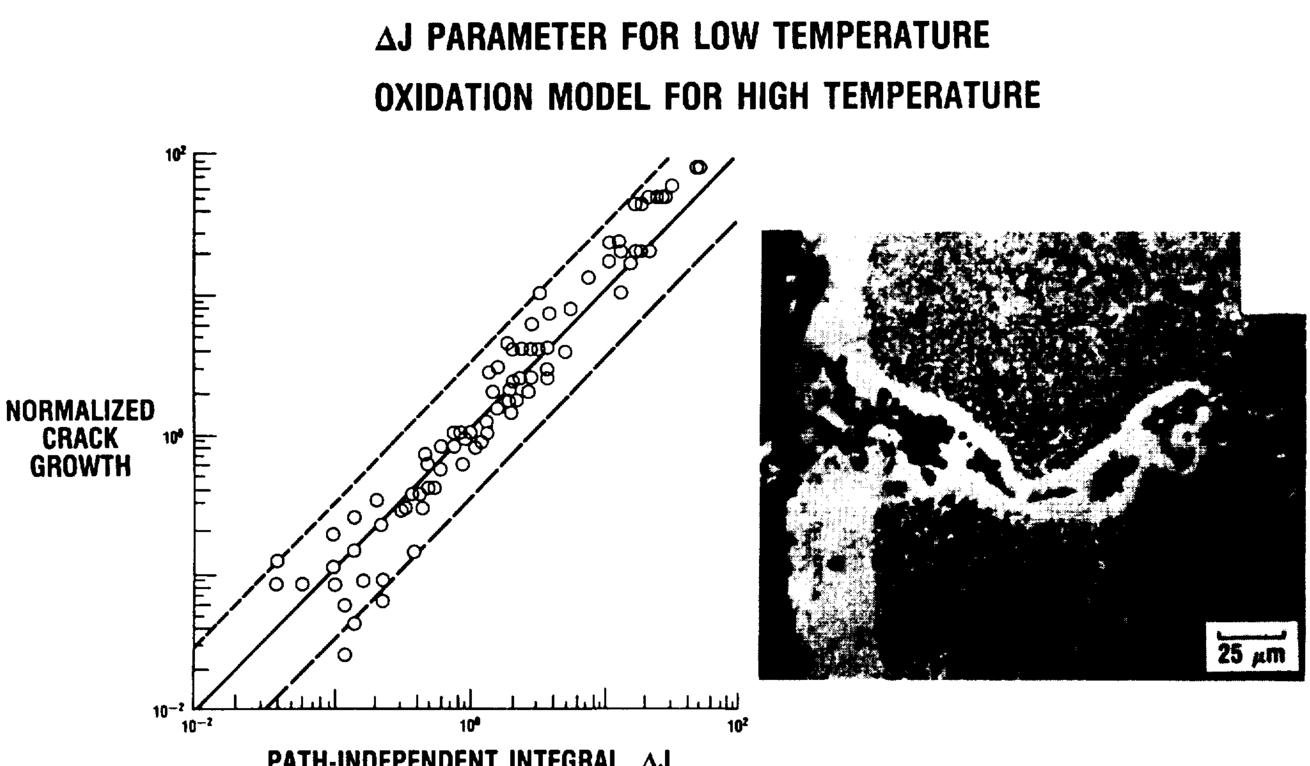

Figure 7. - Isothermal fatigue crack propagation model.

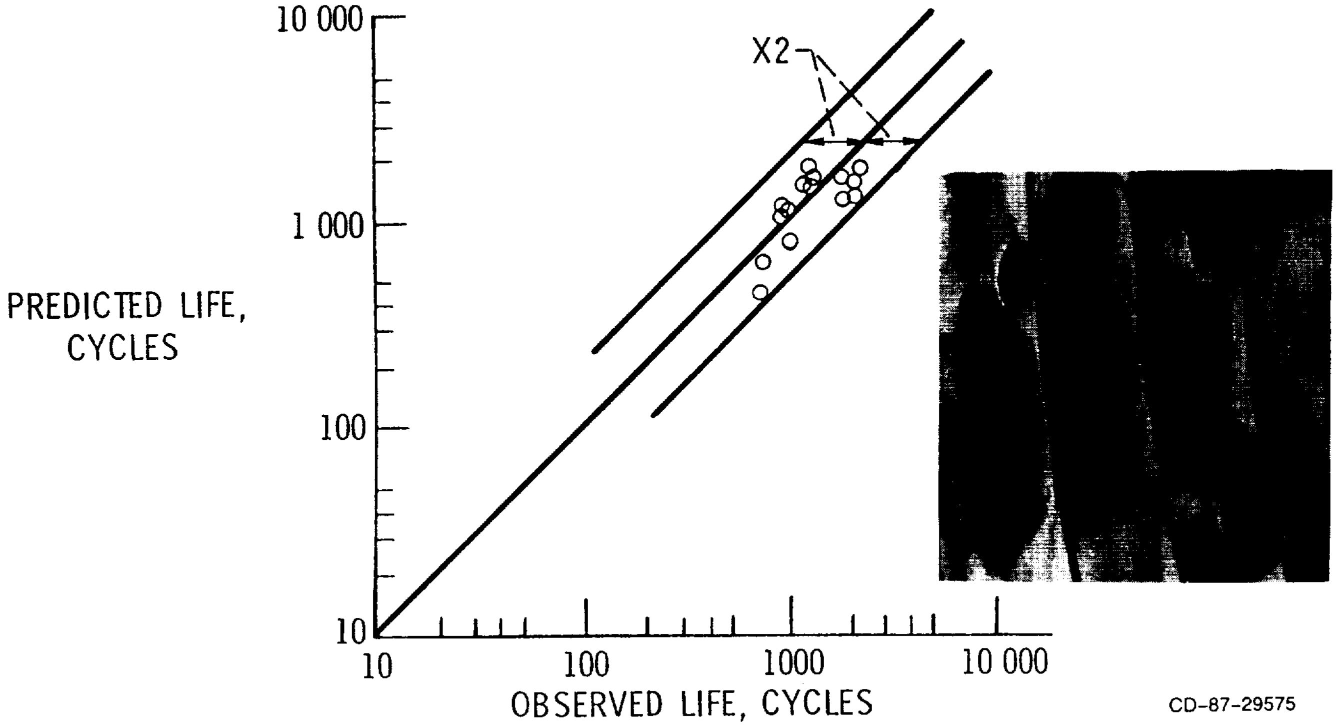

Figure 8. - Accuracy of Pratt & Whitney's version of ductility normalized strain-range partitioning in predicting combustor liner life in high-bypass-ratio engines.

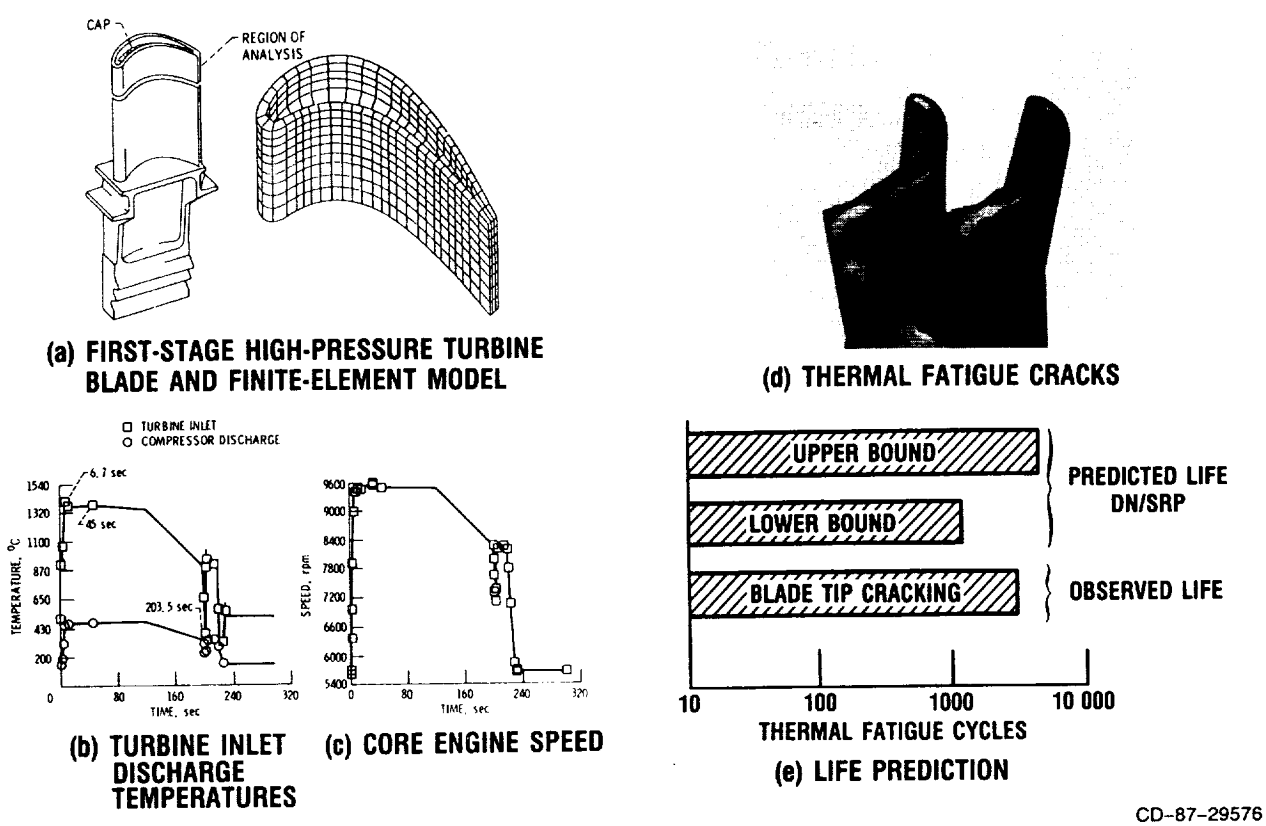

Figure 9. - Turbine blade structural and life analysis.

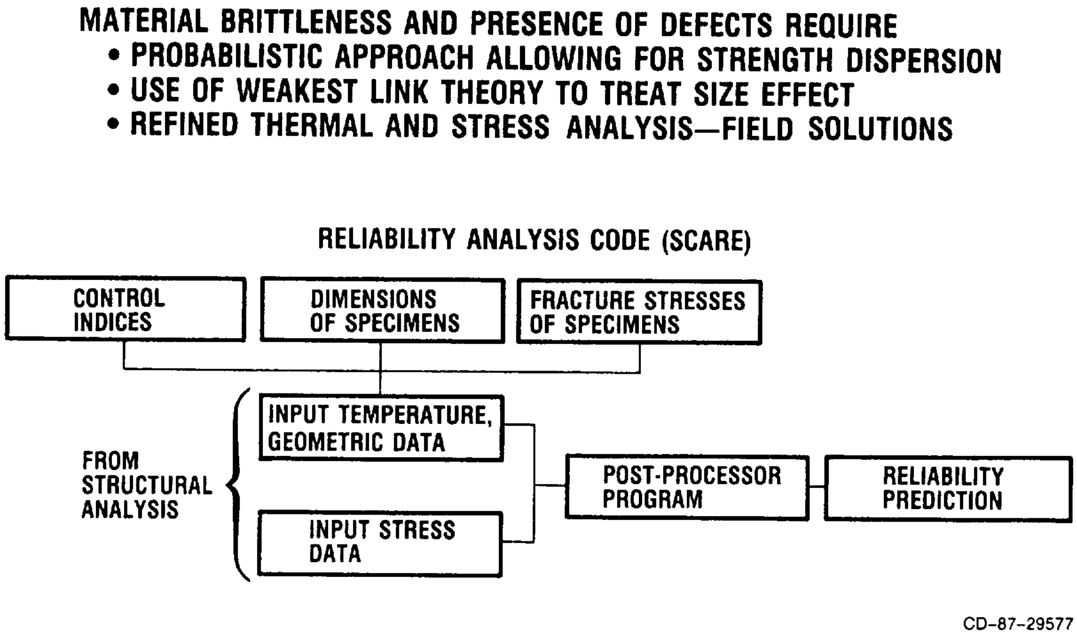

Figure 10. - Ceramics/brittle materials life prediction technology.

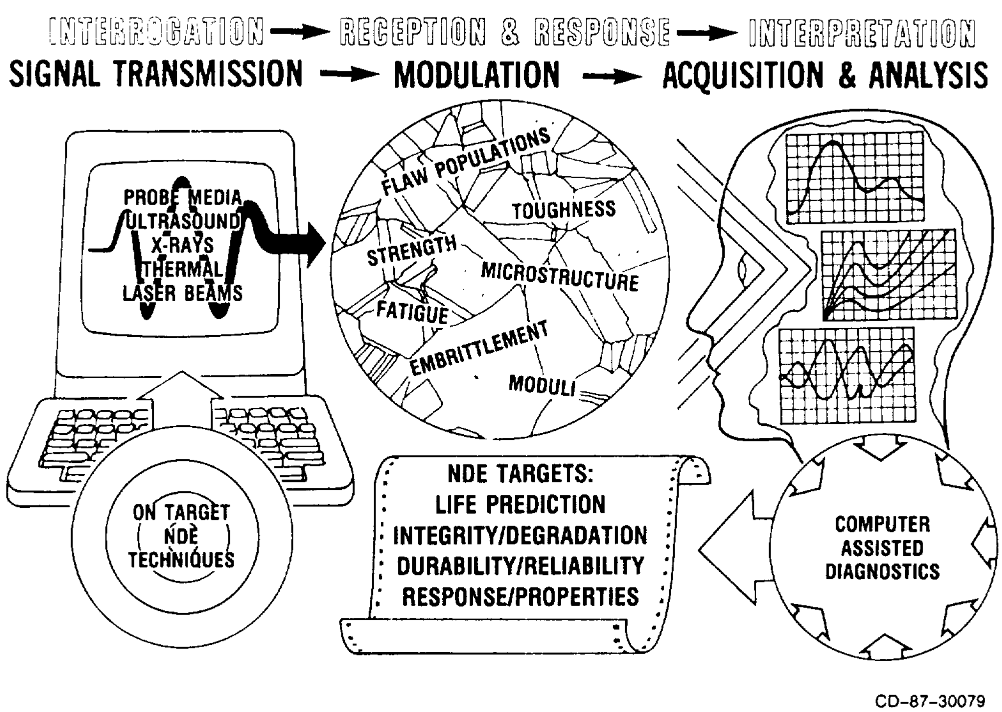

Figure 11. - Nondestructive evaluation (NDE) technology.